TRANSPORTATION RESEARCH CIRCULAR
Number E-C053 July 2003

9th International Bridge Management Conference

Supplement

Orlando Airport Marriott
Orlando, Florida
April 28–30, 2003

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

TRANSPORTATION RESEARCH *CIRCULAR*

Number E-C053, July 2003
ISSN 0097-8515

9th International Bridge Management Conference

Supplement

Orlando Airport Marriott
Orlando, Florida
April 28–30, 2003

Subscriber Category
IIC bridges, other structures, and hydraulics and hydrology
www.TRB.org

Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

Preface

This electronic circular publishes two papers as a supplement to *Transportation Research Circular E-C049* (http://gulliver.trb.org/publications/circulars/ec049.pdf). Papers in both Circulars were presented at the 9th International Bridge Management Conference, held at the Orlando Airport Marriott Hotel, April 28–30, 2003, in Orlando, Florida. The conference was sponsored by the Transportation Research Board in cooperation with FHWA. The objective of the conference was to provide a forum for the exchange of information about the state of the practice and state of the art in bridge management systems between practitioners and researchers in all levels of the public and private sectors. *Transportation Research Circular E-C049* contains papers on bridge management concepts, strategies and health indices, asset management, joints, coatings and concrete repair, life-cycle costs, load testing, utilizing the Internet and performance measures, deterioration and reliability, future directions and challenges in bridge management systems, management system implementation, safety and serviceability, scour modeling and experiences, expert systems and uncertainties, and concrete deterioration. The papers in this Circular have not been subjected to the TRB peer review process.

Contents

Dynamic Load Tests in Bridge Management

JAN BIEŃ
JOZEF KRZYZANOWSKI
PAWEL RAWA
JAROSLAW ZWOLSKI
Wroclaw University of Technology
Institute of Civil Engineering

The potential application of dynamic test results in the bridge management process is considered. The classification of the bridge dynamic tests, based on the method of vibration excitation, is proposed and four main types of tests are distinguished: excitation by traffic, by special vehicles, by force-generating devices, and by means of special techniques. All the considered testing methods are illustrated by examples of the tests preformed by the authors. Special attention is paid to the possibilities of damage detection by means of monitoring the bridge dynamic parameters. Advantages and disadvantages of the presented testing methods are discussed taking into account their usefulness in computer-based bridge management systems.

Bridge structures are exposed to various dynamic loads, e.g. moving live loads, time varying wind loads, etc. The dynamic effects are taken into account while designing bridges and play an important role during the whole life of the structures. The results of the experimental dynamic analysis carried out for many years offer valuable information for comprehensive bridge management (*1–6*). The main methods of dynamic bridge testing and their potential applications in computer-based bridge management systems (BMS) are presented in Figure 1. Two basic types of bridge dynamic tests can be distinguished in the proposed classification: structure dynamic response tests and structure vibration tests.

Dynamic response tests are performed to obtain dynamic characteristics of the bridges under normal traffic or under special vehicles with controlled parameters. These types of tests enable the determination of the following parameters:

- Stresses and strains in the bridge components—the basic data for fatigue analysis;
- A dynamic load factor (dynamic load allowance)—a measure of bridge dynamic sensitivity; and
- Vibration frequencies, mode shapes, vibration amplitude and damping under the live loads.

In the vibration tests special force-generating devices or other special techniques are used for the excitation of the bridge vibration. The main goal of this kind of test is as follows:

- The determination of the natural frequencies of bridge vibration,
- The identification of the corresponding mode shapes, amplitudes and damping characteristics of the structure.

The results of both types of dynamic tests include important information, which can be used as tools supporting selected elements of the bridge management process (Figure 1):

- The fatigue analysis based on experimental data;
- The analysis of bridge serviceability taking into account the users comfort (vibration frequency, amplitude, acceleration, possibility of resonance occurrence, etc.);
- The stiffness analysis (displacements under traffic loads, experimental verification of theoretical models, etc.);
- The detection of bridge damages based on the identification of changes in structure dynamic characteristic; and
- Monitoring forces in cables (e.g., in cable-stayed bridges) or in other external prestressing tendons.

The characteristics of the bridge dynamic response and bridge natural vibration, based on the results of experimental tests, can be applied for

- The evaluation of the bridge condition (conformity with designed dynamic parameters, serviceability, dynamic sensitivity, etc.);
- Monitoring the bridge condition based on the systematic control of structure dynamic parameters;
- Updating the degradation model of the bridge structure; and
- The optimization of the planning process in BMS.

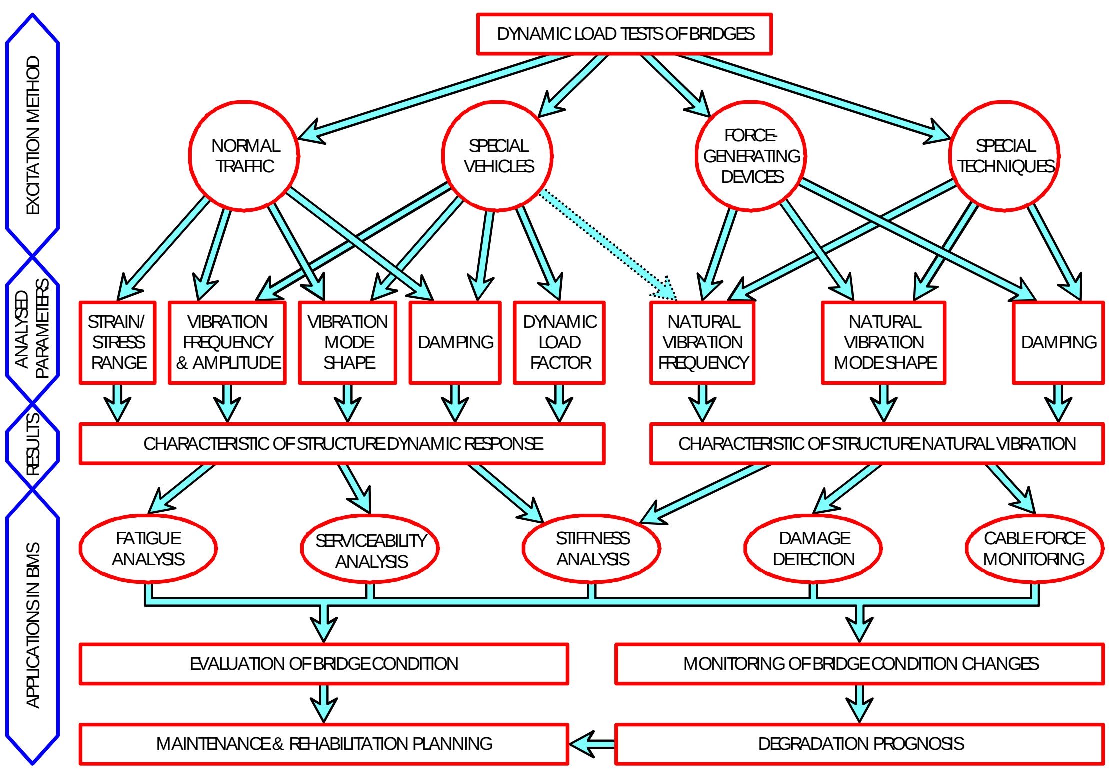


FIGURE 1 Dynamic load tests of bridges and their applications in BMS.

Each of the considered testing methods has specific advantages and disadvantages, which are discussed below based on the examples of tests performed by the authors.

DYNAMIC TESTS UNDER TRAFFIC

Dynamic tests under normal road or railway traffic are performed to identify the dynamic response of the bridge structure to real live loads, for example, Casas and Aparicio (*2*). This type of dynamic tests has the following main characteristics:

- Random nature of loads during the test;
- The vibrating mass of the structure is increased by the mass of the vehicles on the bridge and the dynamic parameters are determined for such a system;
- Vehicles are continuously moving along the bridge, which complicates the identification of the vibration forms; and
- Tests can be performed without any disturbances in the normal operation of the bridge.

An example of the monitoring of suspension bridge vibration under road traffic is presented in Figure 2 and Figure 3. The laser-based measuring system applied in this test (*7, 8*) consists of the laser transmitter and the position-sensitive receiver connected to a laptop computer (Figure 2*a*). The laser transmitter is placed on a solid base outside the bridge at a distance up to 300 m (Figure 2*b*) and the receiver is located on the tested bridge (Figure 2*c*).

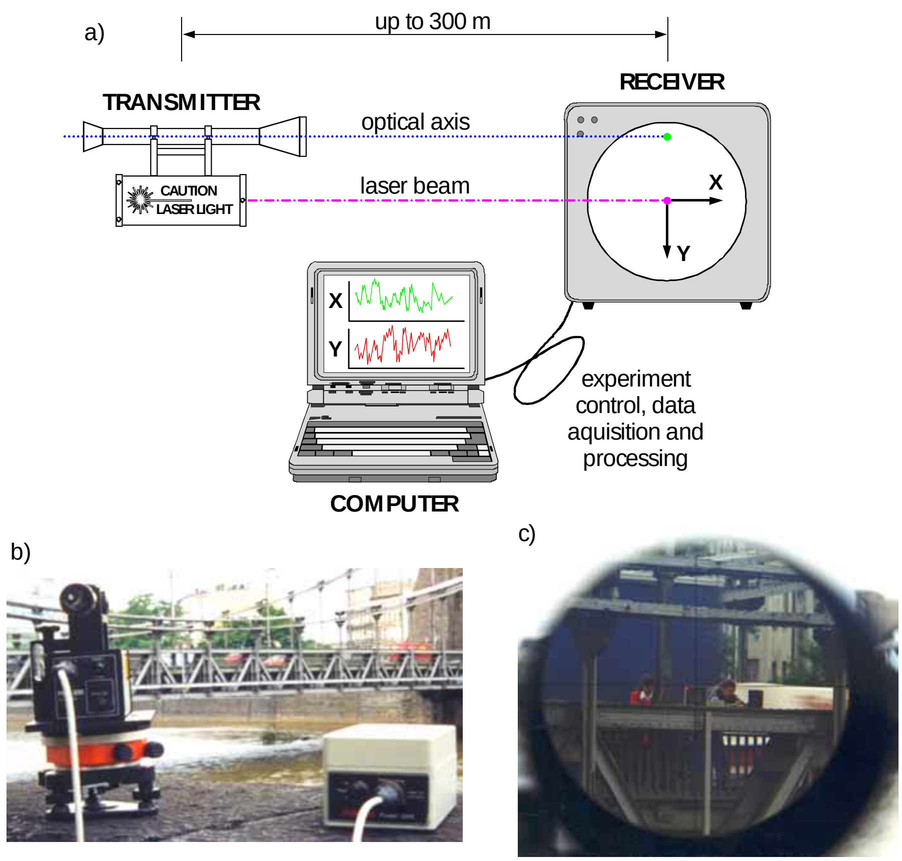


FIGURE 2 Laser-based displacement measuring system: (*a*) configuration, (*b*) transmitter on the riverside, and (*c*) receiver located on the tested bridge.

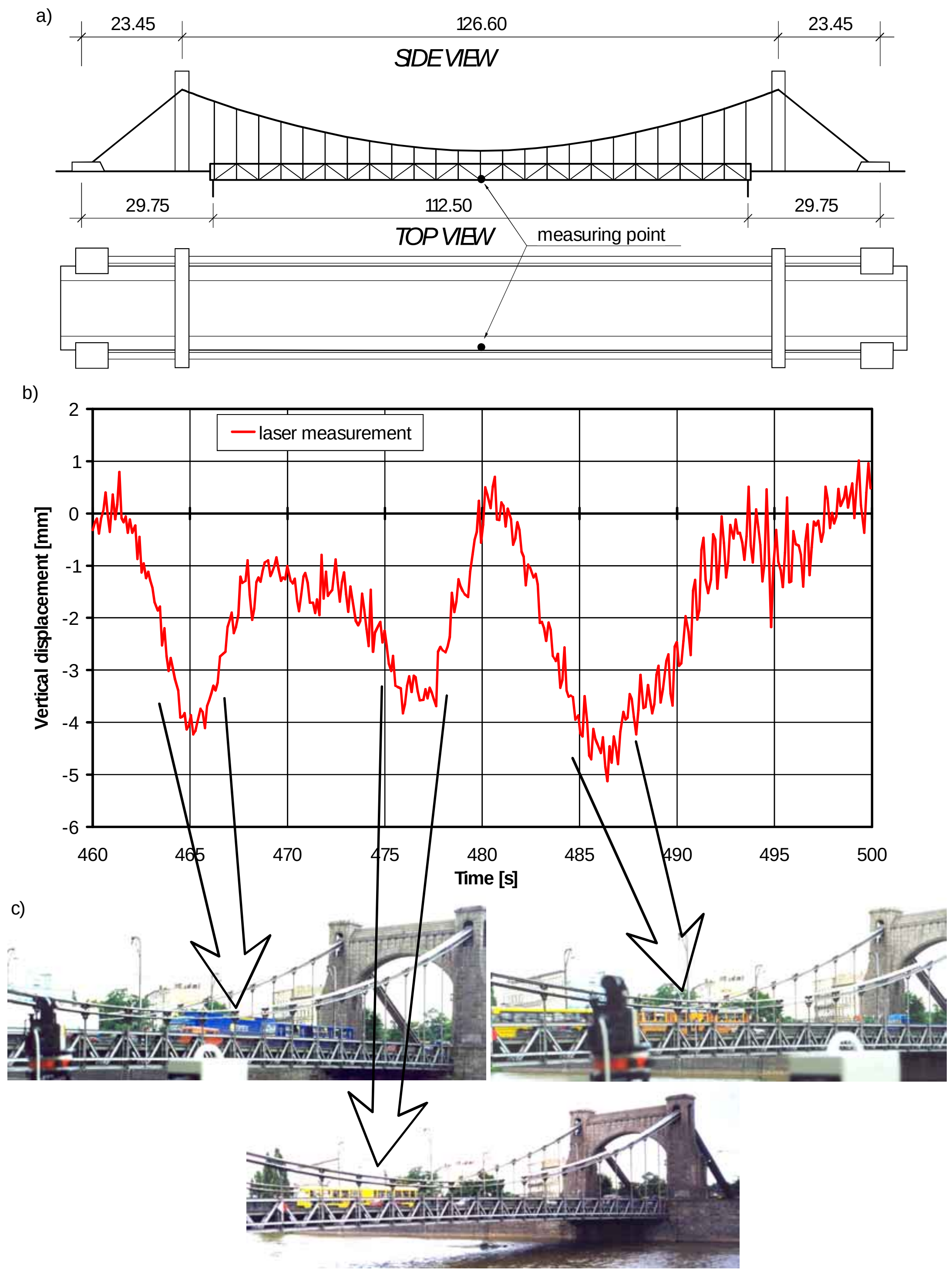


FIGURE 3 Vibrations of Grunwaldzki Bridge over Odra River in Wroclaw: (*a*) bridge scheme and location of measuring point, (*b*) vertical displacements under traffic, and (*c*) loads in selected moments of the test.

The position of the laser beam on the sensitive screen is continuously recorded in two-dimensional space. Vertical displacements of the measuring point in the middle of the span (Figure 3*a*) are presented in Figure 3*b*. The measuring system has been coupled with a camera, which enables the identification of the loads configuration during the test (Figure 3*c*).

DYNAMIC TESTS BY MEANS OF SPECIAL VEHICLES

In many countries dynamic tests under special vehicles are standard proof load tests before opening the bridge for use. Heavy trucks or locomotives with controlled parameters (axle loads, geometry, speed, etc.) are usually used as dynamic loads, e.g. (*5*, *9*, *10*, *11*). The most important conditions of this type of test are as follows:

- The main parameters of the dynamic loads are known and can be controlled;
- The vibrating mass of the bridge is influenced by the moving mass of the vehicle(s);
- The moving vehicles complicate the identification of the vibration forms; and
- Tests have to be performed without any other dynamic loads of the bridge.

The results of the tests of the arch viaduct A016 (*11*) over the highway A4 (Figure 4) are presented as an example. Vertical displacements of the measuring points A and B, located on both sides of the deck in the middle of the span, are shown in Figure 5. The results of the test with normal plain road surface are presented in Figure 5*a* and displacements during the test with artificial "bump" (height 3 cm) – in Figure 5*b*.

Dynamic load factors for various speed of the truck—based on the experimental data —are presented in Figure 5*c*. Five trucks of the same type and the same parameters (axle loads, geometry) were used for each test. Differences within the same test are probably caused by the various technical conditions of the vehicles. Higher dynamic load factors during "bump" tests show the sensitivity of the structure to the damages of the road surface (e.g., pot holes).

FIGURE 4 Arch viaduct A016 over highway A4 during load tests.

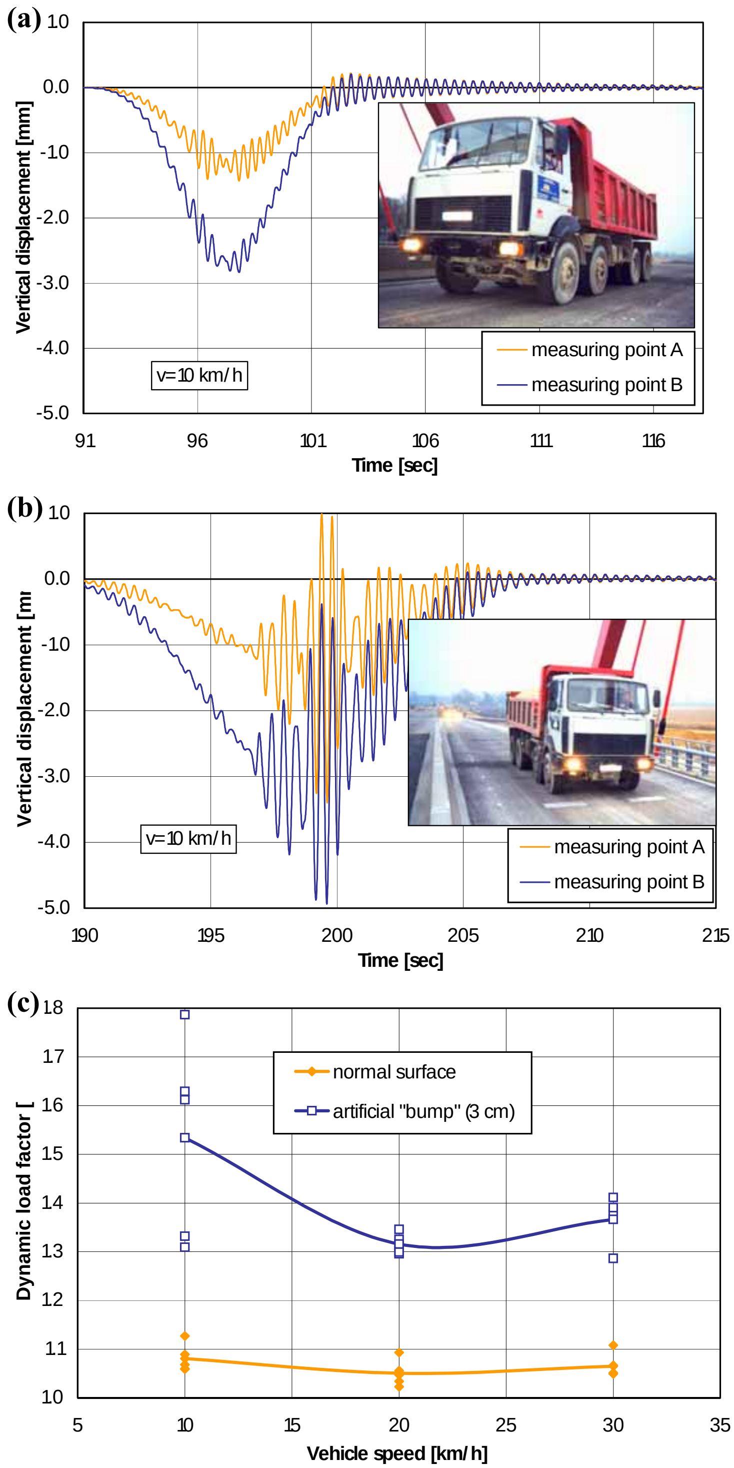


FIGURE 5 Dynamic load tests of viaduct A016 under special vehicle: (*a*) vertical displacement of the deck—test with normal road surface, (*b*) vertical displacement of the deck—test with artificial "bump" (height 3 cm), and (*c*) dynamic load factors for various speeds of the vehicle.

VIBRATION TESTS USING PERIODIC EXCITATION

Vibration tests are conducted mainly by means of force-generating devices (*1*, *4*, *12*). The application of a mechanical vibration exciter enables:

- Controlling the frequency of the excitation force;
- Free selection of the excitation force location on the tested structure;
- Identification of the resonance frequency while scanning the wide range of the excitation frequencies (mass of the force-generating device can be neglected);
- Keeping the tested structure in a steady-state for defined conditions of excitation, including resonant vibration;
- Repeatability of the excitation parameters, even after a long time; and
- Easy transport of the set-up for test execution and short time of disturbances in the traffic during the test.

During the last few years two types of force-generating devices were constructed and tested by the Institute of Production Engineering and Automation and the Institute of Civil Engineering of the Wroclaw University of Technology (*6*, *13*):

1. Vibration exciter based on the rotation of the unbalanced masses for frequency between 0 and 15 Hz;
2. Inertial exciter for lower frequencies, between 0 and 5 Hz.

Up to now twelve various types of bridge structures have been tested by means of the exciters. Taking into account accumulated experience, two procedures of the bridge vibration tests have been proposed: a preliminary test addressed to new bridges and a monitoring test dedicated to bridge structures under operation.

The proposed procedure of initial testing of a new or rehabilitated bridge by means of the vibration exciter is presented in Figure 6. The main steps of the test are explained on the example of the footbridge B027 (*12*) shown in Figure 7:

- A theoretical analysis of the structure (FEM) to define natural vibration frequencies and corresponding mode shapes;
- The determination of the most effective position of the vibration exciter on the tested bridge and selection of the measuring points;
- Experimental detection of the resonance frequencies and measurement of the corresponding dynamic parameters; vertical displacements of the bridge deck are presented in Figure 8*a* and results of the frequency analysis for excitation frequency 4.27 Hz in Figure 8*b*; and
- Comparison of the experimental and theoretical data and storing the dynamic parameters of the structure in a computer-based BMS as a basis for the next tests.

The vibration tests are especially useful for monitoring bridge condition. The systematic control of changes in the dynamic parameters enables detection of bridge condition changes. The proposed testing procedure is presented in Figure 9. The procedure is illustrated by the destructive test of the composite bridge D010 on the highway A4, shown in Figure 10.

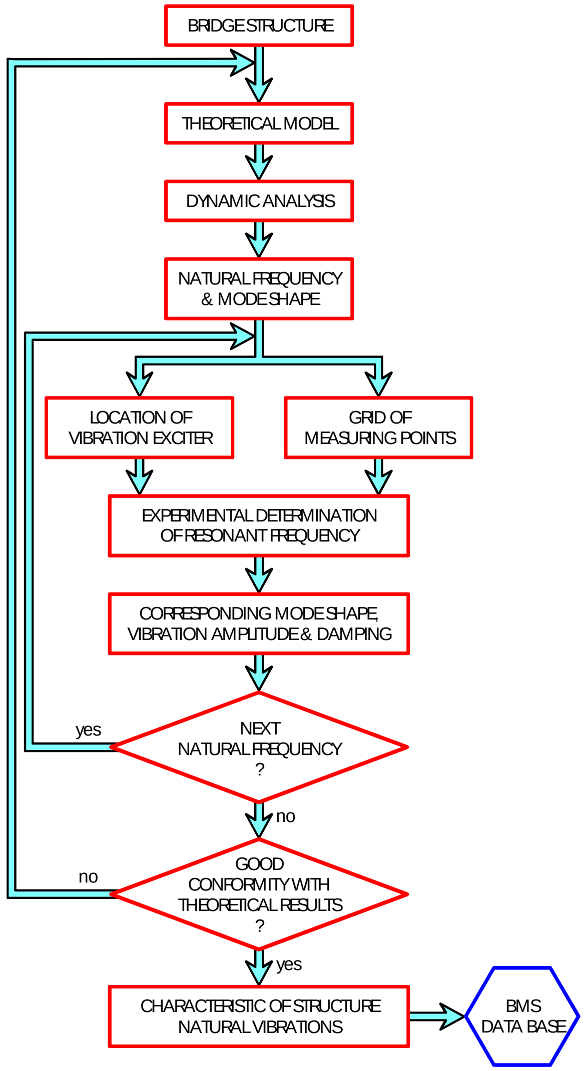


FIGURE 6 Procedure of initial bridge testing by means of vibration exciter.

In the first step the bridge has been tested according to the procedure presented in Figure 6 to define the dynamic characteristic of the structure without damages. In the next step one of the steel girders has been cut (Figure 11*a*) and the vibration tests have been conducted in the following sequence for each level of damage severity:

- The excitation of the bridge with the resonant frequency determined for the structure without damages;
- The determination of changes in vibration amplitude and mode shape due to the introduced damages;
- The determination of changes in the resonant frequency of the damaged structure; and
- The measurement of the vibration amplitude and mode shape for new resonant frequency of the bridge.

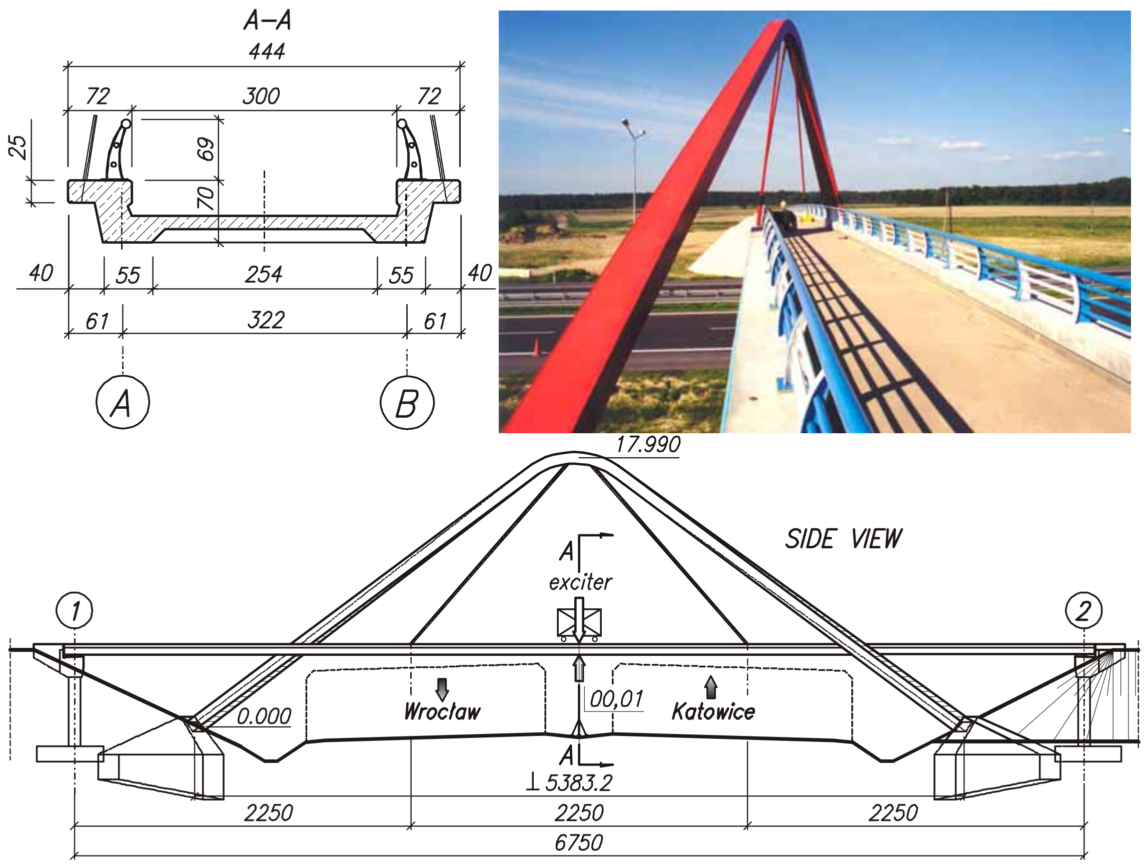


FIGURE 7 Tested footbridge B027 over highway A4.

The damages affect the amplitude of the bridge vibrations. Figure 11*b* presents the relationship between the severity of the damage (diminishing of the span stiffness) and the amplitude of vibrations. The presented results have been obtained for constant frequency of excitation and equal resonant frequency of the structure without damages. An amplitude of 0.25 mm for a structure without any damages diminished to 0.16 mm for 12.7 % of stiffness reduction and to 0.04 mm by 19.5 % of reduction.

Changes of the resonant frequencies for two levels of reduction of the span bending stiffness are presented in Figure 11*c*. For a structure without any damages the frequency is 12.12 Hz and diminished to 11.77 Hz (in case of 12.7 % stiffness reduction) and to 11.07 Hz for 19.5 % reduction of the stiffness.

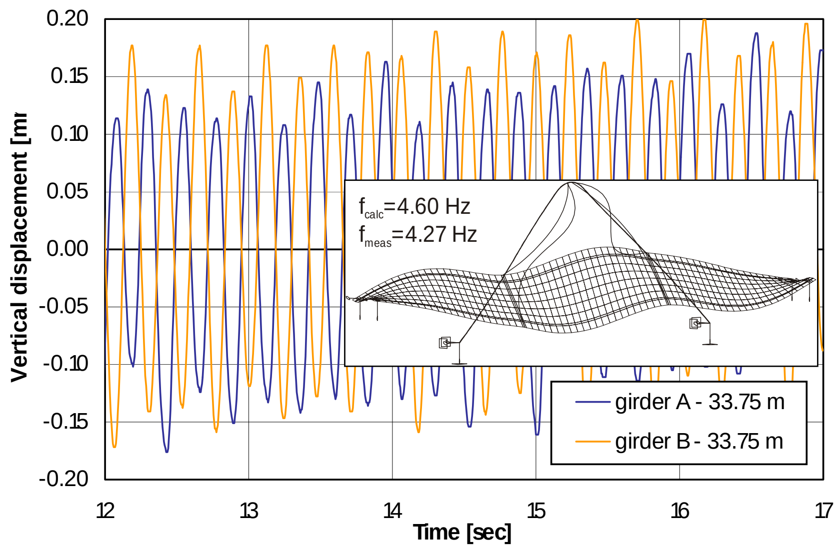
The analysis of the test results show that the vibration amplitude of the tested structure is more sensitive to the considered damages than resonant frequency.

SPECIAL TECHNIQUES IN DYNAMIC TESTING

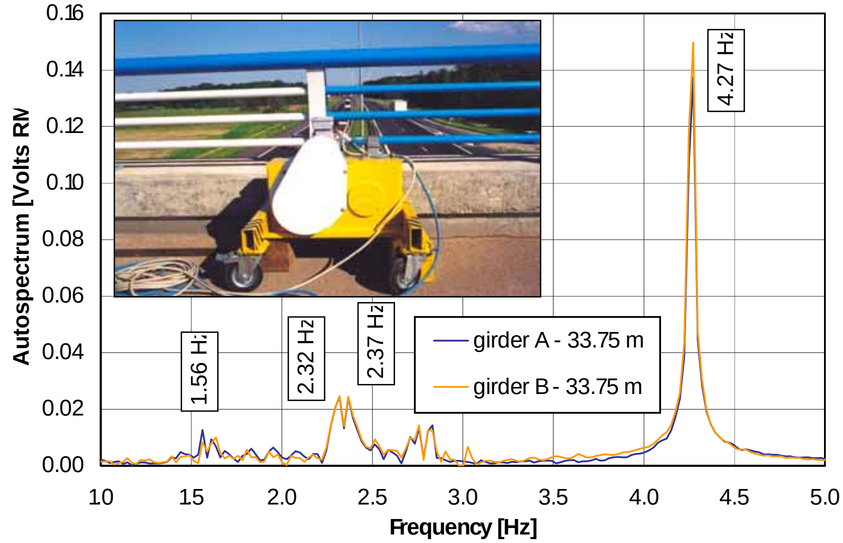
Sometimes individual conditions of the bridge dynamic test need the application of a special technique of structure excitation. The excitation force, usually of the impulse nature, can be produced by

- A sudden release of the applied deflection,
- Stopping of heavy vehicle, or
- Dropping a mass on the tested structure, and so on.

For instance, special excitation methods can be effectively applied for controlling the internal forces in the cables of the cable-stayed bridges. As an example the selected results of the tests of the bridge over Vistula River in Warsaw (Figure 12*a*) are presented. The sudden release of the deflection of the cable (Figure 12*b*) was used for the vibration excitation. Free vibrations of the tendon were measured by means of the set of accelerometers placed on the cable (Figure 12*b*).



(a)



(b)

FIGURE 8 Vibration test of footbridge B027: (*a*) vertical displacement of the deck and calculated as well as measured vibration frequency and mode shape, and (*b*) vibration exciter on the tested structure and results of the frequency analysis.

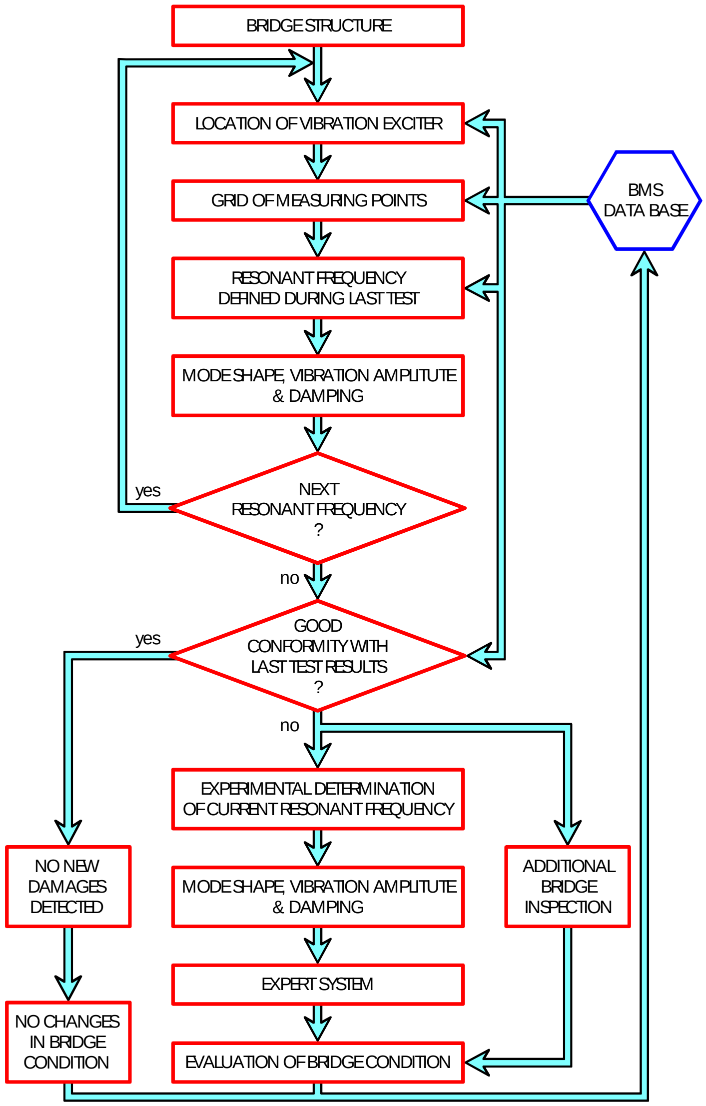


FIGURE 9 Procedure of monitoring bridge condition by means of vibration exciter.

Two tests of the cable No. 7, performed during preliminary load before opening the bridge to traffic (*10*), are presented:

- The vibration test of the cable before the static tests (no live loads on the bridge) (Figure 13*a*); and
- The vibration test during static proof load of the main span 4-5.

The recorded changes in the vibration frequencies during both tests can be observed in Figure 13*b*. The axial forces in the tested cable, determined from the experimental data and calculated theoretically, are compared in Table 1. The conformity of the results seems to be satisfactory.

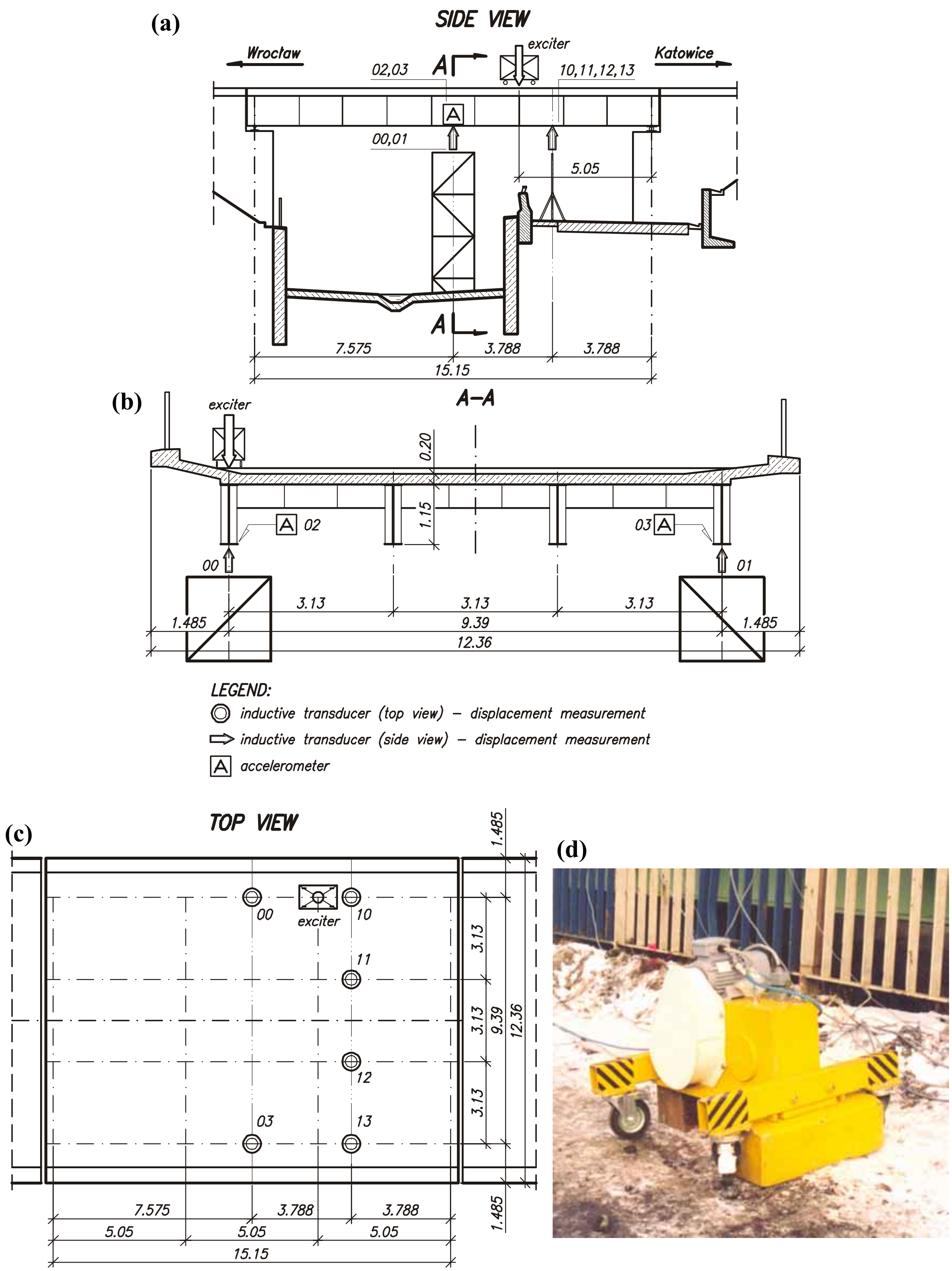
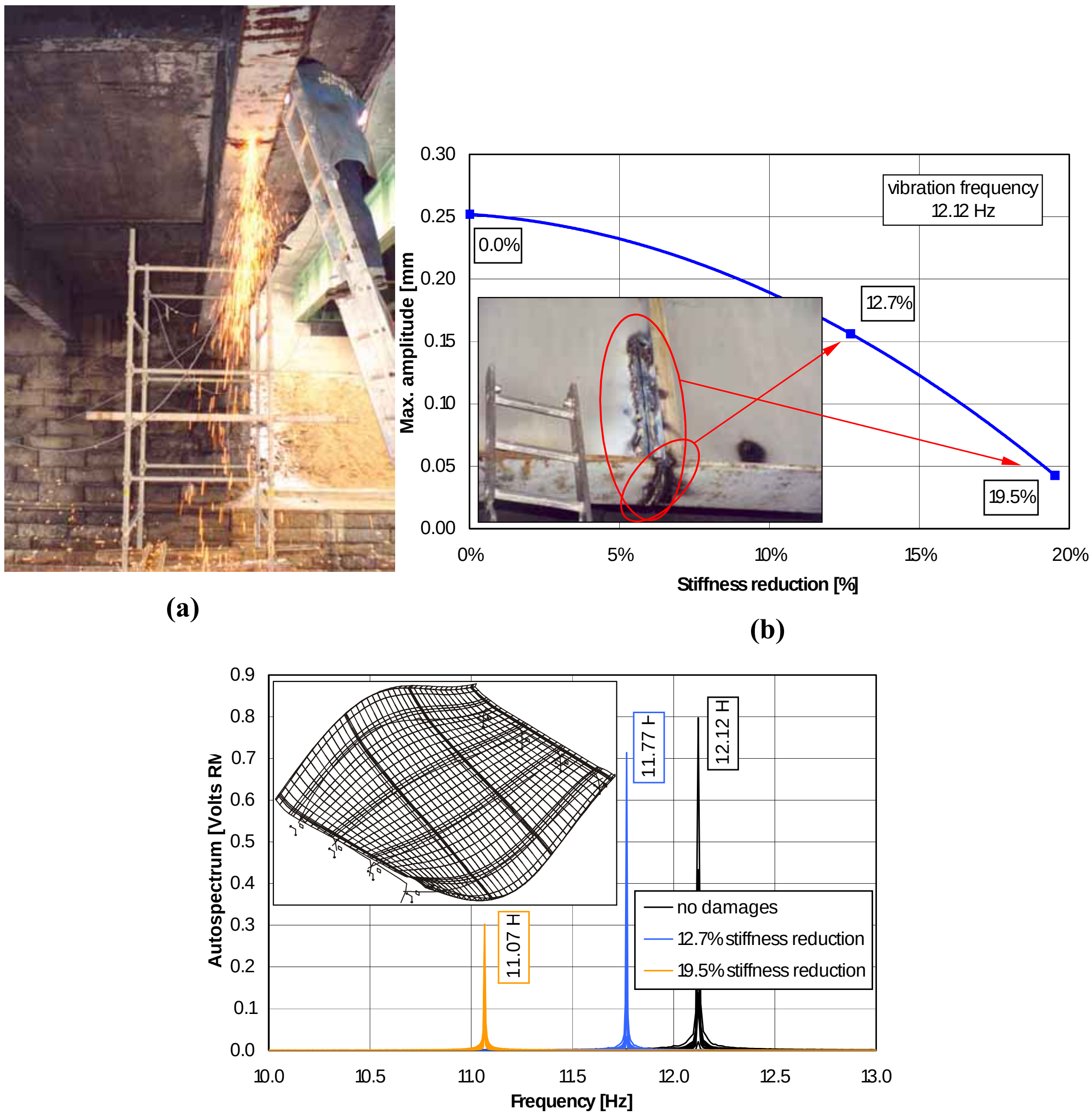


FIGURE 10 Bridge D010 on the highway A4: (*a*) side view, (*b*) cross-section A-A, (*c*) top view, and (*d*) vibration exciter on the bridge deck.



(c)

FIGURE 11 Destructive test of bridge D010: (*a*) cutting of the steel girder, (*b*) changes of the vibration amplitude as a function of bending stiffness diminishing, and (*c*) changes of the resonance frequency due to span stiffness reduction for showed vibration form.

CONCLUSIONS

Growing experience in dynamic testing of bridges and—on the other hand—the need for more and more efficient methods of bridge management enable the formulation of the following conclusions:

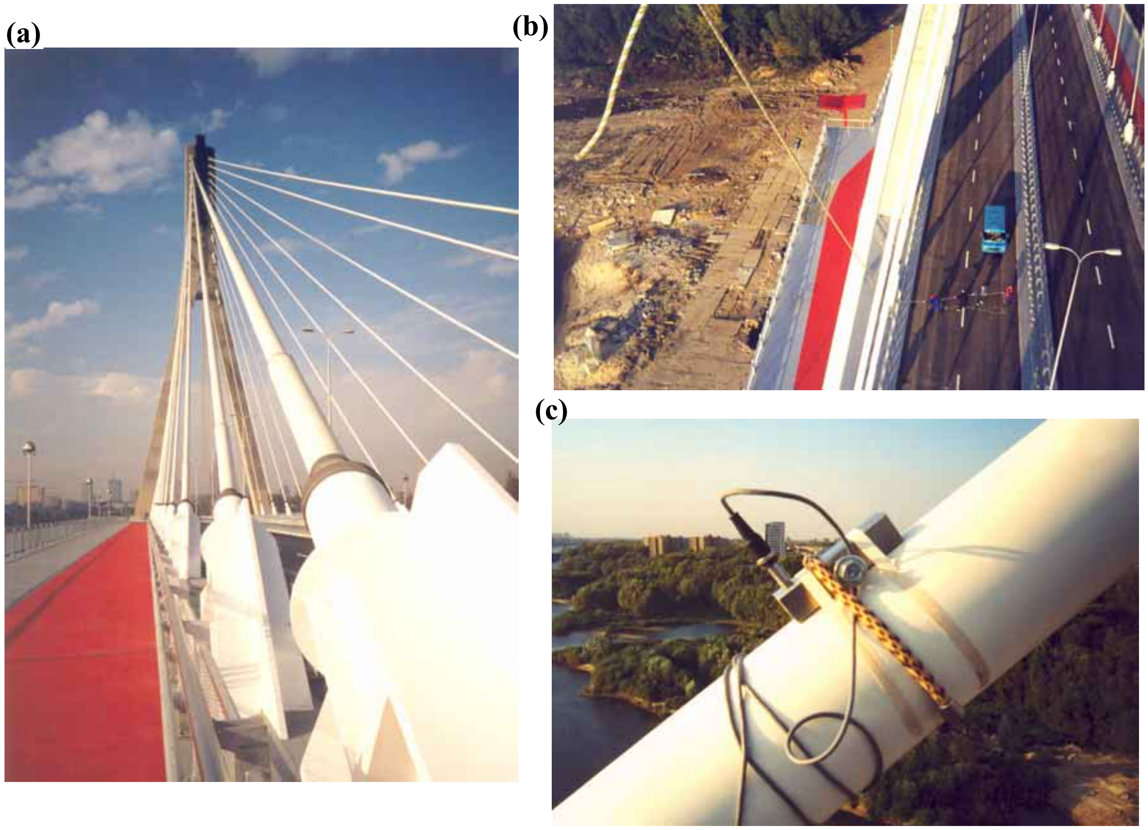


FIGURE 12 Cable-stayed bridge over Vistula River in Warsaw: (*a*) pylon and cable system, (*b*) cable deflection applying, and (*c*) accelerometers in the middle of cable length.

- All considered types of the bridge dynamic tests offer valuable and often unique information which can be used in bridge management;
- Various excitation methods and advanced measurement technologies enable precise recording and analyzing of the bridge vibration phenomena;
- The dynamic parameters of the bridge structures are sensitive to the structural damages and enable the detection of the damages which are difficult to identify by means of the other methods;
- The systematic monitoring of changes in bridge dynamic characteristic can be a useful tool for evaluation of structure condition;
- The considered dynamic tests are relatively inexpensive and cause minimal disturbances of traffic;
- The utilization of the dynamic test results in the BMS requires standardization of the test procedures and measurement techniques to make all the results comparable; and
- The unified interpretation of the test results can be ensured by the creation of a specialized knowledge-based expert systems.

TABLE 1 Tests of Tendon No. 7 of Bridge over Vistula River in Warsaw (South Side)

Bridge load	Experimental results		Theoretical analysis
	First frequency of vibration [Hz]	Tendon force [MN]	Tendon force [MN]
Dead load	1.282	4.447	3.995
Dead load and proof load	1.416	5.425	5.003

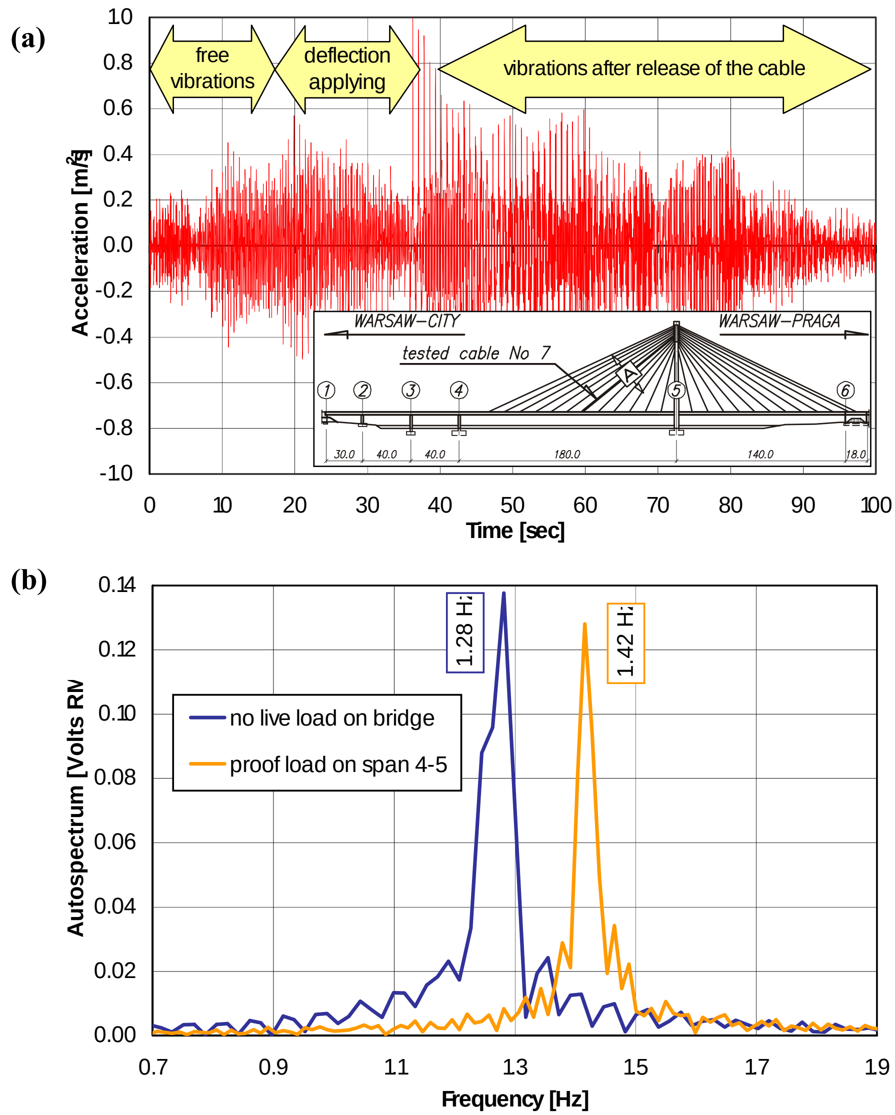


FIGURE 13 Tests of the bridge over Vistula River in Warsaw: (*a*) acceleration perpendicular to the cable axis and tested cable location, and (*b*) changes in vibration frequencies depending on bridge load.

ACKNOWLEDGMENT

The financial support of the construction and testing of the vibration exciters by the Polish State Committee for Scientific Research is gratefully acknowledged.

REFERENCES

1. Flesch, R. G., and K. Kernbichler. A Dynamic Method for the Safety Inspection of Large Prestressed Bridges. In *Bridge Evaluation, Repair, and Rehabilitation* (Andrzej S. Nowak, ed.), Kluwer Academic Publishers, 1990, pp. 175–185.
2. Casas, J. R., and A. C. Aparicio. Dynamic Testing of Bridges Using Traffic-Induced Vibration. In *Bridge Evaluation, Repair, and Rehabilitation* (Andrzej S. Nowak, ed.), Kluwer Academic Publishers, 1990, p. 405–420.
3. Paultre, P., and J. Proulx. Dynamic Testing of Large-Scale Structure. *Structural Engineering International*, No. 1, 1997, pp. 29–34.
4. Salawu, O. S. Assessment of Bridges: Use of Dynamic Testing. *Canadian Journal of Civil Engineering*, Vol. 24, 1997, pp. 218–228.
5. Broquet, C., and E. Bruhwiler. In situ and Model Tests and Numerical Analysis of a Curved Cable-Stayed Bridge. *Structural Engineering International*, No. 1, 1999, pp. 57–62.
6. Bień, J., M. Gladysz, and P. Rawa. Vibration Tests of Bridge Structures. First International Conference on Bridge Maintenance, Safety, and Management, IABMAS, Barcelona, Spain, 2002, pp. 105-106 + CD.
7. Bień, J., and P. Rawa. Laser Based Testing and Monitoring of Large Bridges. Structures Congress of the American Society of Civil Engineers, Structural Engineering in the 21st Century, New Orleans, 1999, pp. 332–335.
8. Bień, J., and P. Rawa, Laser Measurement of Static and Dynamic Displacement of Bridge Structures (in Polish). *Inzynieria i Budownictwo*, No. 3/4, 2002, pp. 161–166.
9. Bień, J., P. Rawa, and J. Zwolski. Proof Load Tests of Highway Bridges (in Polish). *Inzynieria i Budownictwo*, No. 11, 2001, pp. 661–668.
10. Bień, J., J. Kmita, P. Rawa, and J. Zwolski. Tests of Swietokrzyski Bridge over Vistula River in Warsaw (in Polish). *Inzynieria i Budownictwo*, No. 3/4, 2002, pp. 166–170.
11. Bień, J., P. Rawa, and J. Zwolski. Load Tests of Arch Viaducts over the Highway A4 (in Polish). *Inzynieria iBudownictwo*, No. 6, 2002, pp. 316–321
12. Bień, J., J. Kmita, P. Rawa, and J. Zwolski. Highway A4: Part Wroclaw-Nogowczyce. Load Tests of Bridge Structure B027 over Highway A4 – km 218+926.50. Report SPR-60/2001. Wroclaw University of Technology, Institute of Civil Engineering, Wroclaw, Poland, 2001.
13. Bień, J., J. Krzyzanowski, W. Poprawski, W. Skoczynski, and J. Szymkowski. Experimental Study of Bridge Structure Dynamic Characteristics Using Periodic Excitation. International Conference on Noise and Vibration Engineering ISMA 2002, Leuven, Belgium, 2002, pp. 555–562.

Hybrid Knowledge Representation in Bridge Management Systems

JAN BIEŃ
PAWEL RAWA
Wroclaw University of Technology
Institute of Civil Engineering

Development of computer technology enables the implementation of expert tools supporting decision processes in bridge management systems. The proposed expert tools utilize both the data base and knowledge base of the system. Decisions in bridge management are very often based on a mixture of precise data and fuzzy or uncertain information. It requires proper technology for information acquisition, representation, and processing. Presented is the technology of hybrid knowledge representation, integrating symbolic and nonsymbolic knowledge representation. The proposed technology of the multilevel hybrid network enables the integration of various techniques in one computer tool. According to the problem that should be solved and to the type of available information the hybrid network can be built of the neural, fuzzy, and functional components.

In the traditional computer-based bridge management systems (BMS) information is stored as data in the form of the database. The development of computer technology currently enables representation of information also in the form of an advanced knowledge base. A general diagram of the information flow in the data- and knowledge-based BMS is presented in Figure 1.

The information coded in the form of data is stored and processed in the computer system and after interpretation in a specific context, is used in decision processes. Knowledge representation in the computer-based BMS needs much more complex procedures. The following main steps of these procedures can be distinguished (*1*):

- Selection of the knowledge representation method, corresponding to the form of the available information;
- Acquisition of the knowledge as a special type of the information;
- Construction of the computer knowledge base coupled with the system database;
- Selection of the proper inference mechanisms for each particular application; and
- Analysis and interpretation of the results of the computer reasoning and the application of the conclusions in the decision processes.

The analysis of the information taken into account in bridge management shows that decisions are very often based on the fuzzy information and on the information of various degrees of uncertainty (*1*–*3*). The classification of the information utilized in the BMS, proposed in Bień (*1*), is presented in Table 1. The classification is based on information fuzziness and takes into account two basic aspects: fuzziness of the information definition and fuzziness of the information measure.

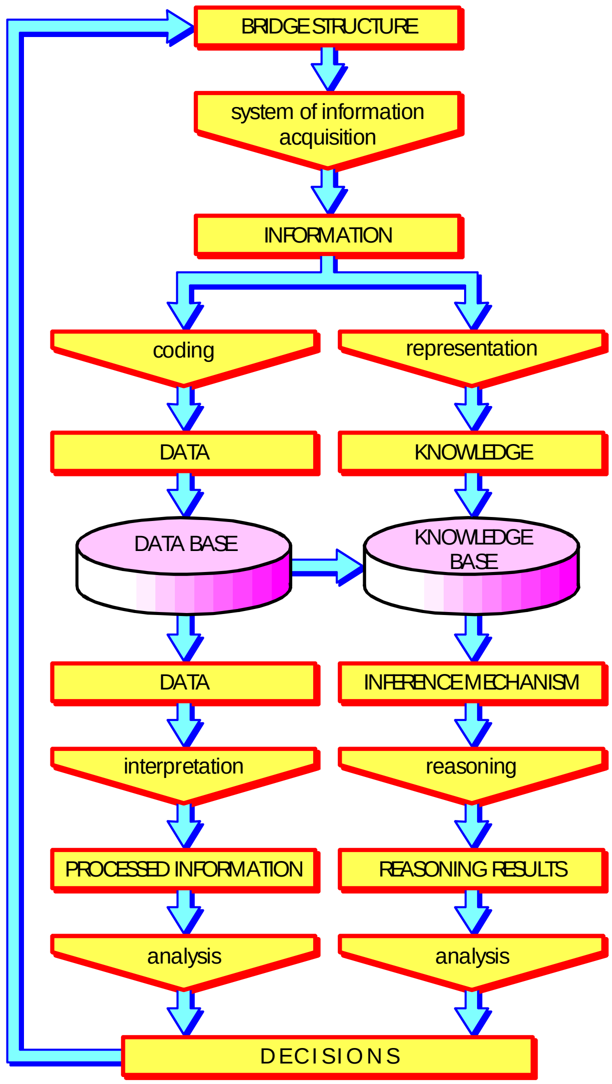


FIGURE 1 Information flow in the data- and knowledge-based BMS.

TABLE 1 Types of Information Utilized in BMS: Classification Based on Information Fuzziness

Definition	**Measure**	
	Precise (P)	**Fuzzy (F)**
Precise (P)	PP	PF
Fuzzy (F)	FP	FF
Undecided (U)	UP	UF

In the proposed classification three types of information definitions are distinguished:

- Precise definitions (P): for example, geometrical parameters or material characteristics, based on standards, manuals, etc.;
- Imprecise, fuzzy definitions (F): for example, technical condition or serviceability, etc., which are partly based on subjective interpretation; and
- Undecided definitions (U): for example, aesthetics of bridge structures, which are completely based on individual, subjective impressions.

The information can be described using two types of measures:

- Precise measures (P) – expressed usually by means of the numbers (e.g., span length: 24 m, condition state: 2, load capacity: 30 t); and
- Fuzzy measures (F): expressed by means of the fuzzy numbers (e.g. about 20 m, between 20 t and 30 t) or by means of the fuzzy linguistic values (e.g. large, intensive, insignificant).

The combination of the three types of information definitions and the two types of information measure creates six classes of information presented in Table 1. All the classes of information are usually used in bridge management.

TECHNOLOGY OF HYBRID NETWORKS

A variety of information types taken into account in the bridge management process require effective tools for data and knowledge acquisition, processing, and utilization. One of the promising methods of knowledge representation seems to be the technology of the multilevel hybrid networks (*1*, *4*, *5*). This technology enables the integration of the various knowledge representation techniques in one expert tool.

The process of the creation of the expert application by means of the hybrid network technology is presented in Figure 2. After the general analysis of the problem and the acquisition of the available knowledge – the architecture of the final network should be designed. Depending on the form and class of the accumulated information (see Table 1) the analyzed problem should be divided into sub-problems. In the next step for each sub-problem a dedicated component of the network is created. All the components are prepared in the form of prefabricated "blocks" which are stored in the library of the computer system and can be used in various networks. In the last step of the creation process the components are connected to one another to form a multilevel network. For the creation of the components and the final network the specialized computer system Neuritis (*1*, *6*) can be used (Figure 3). The system is now available only in a Polish version.

The illustration of the process of the components connecting to obtain a multilevel hybrid network is presented in Figure 4. In the system Neuritis the number of network levels as well as the number of network components are not limited and depend only on application needs.

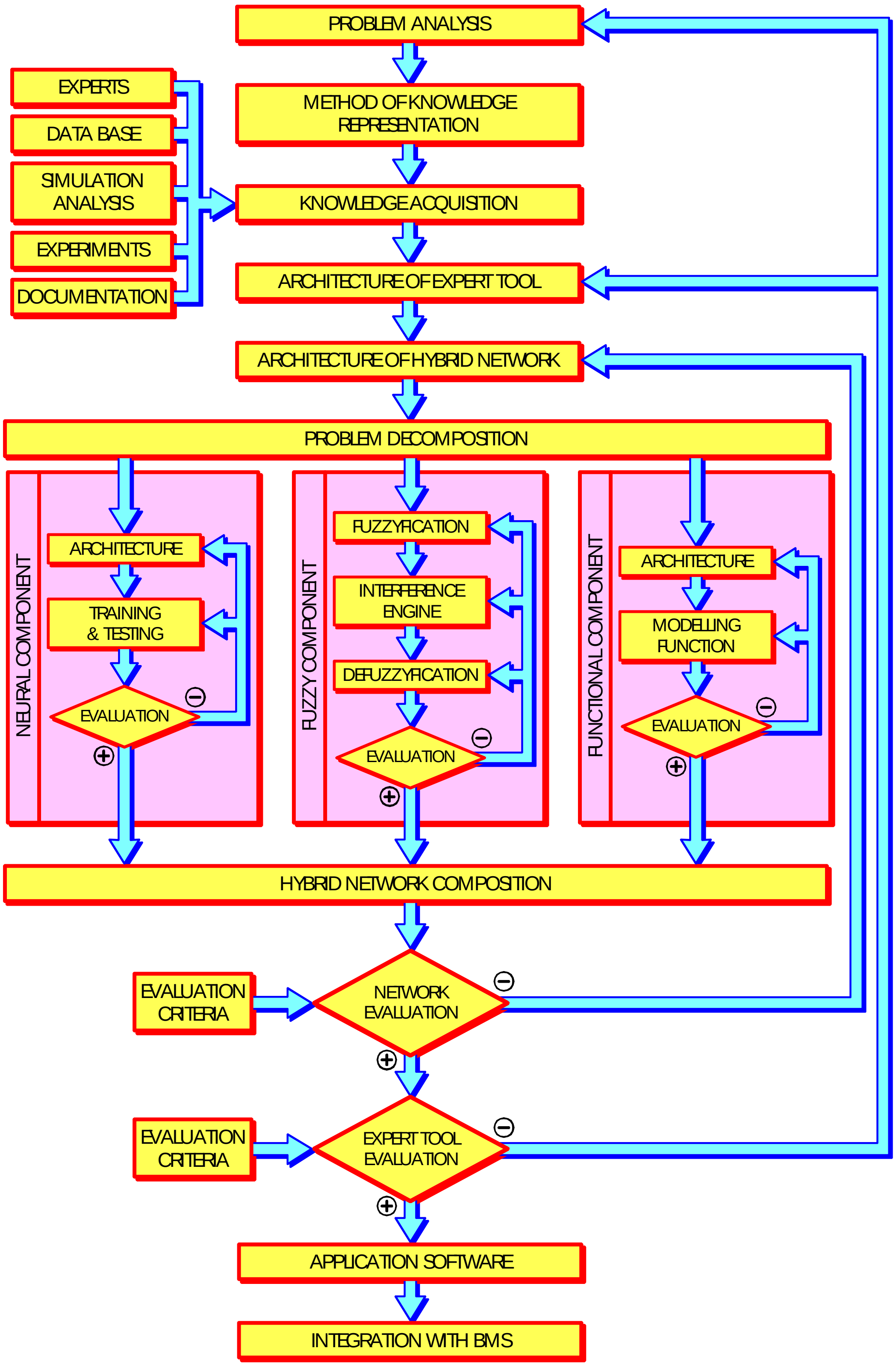


FIGURE 2 Creation of the expert tool with hybrid knowledge representation.

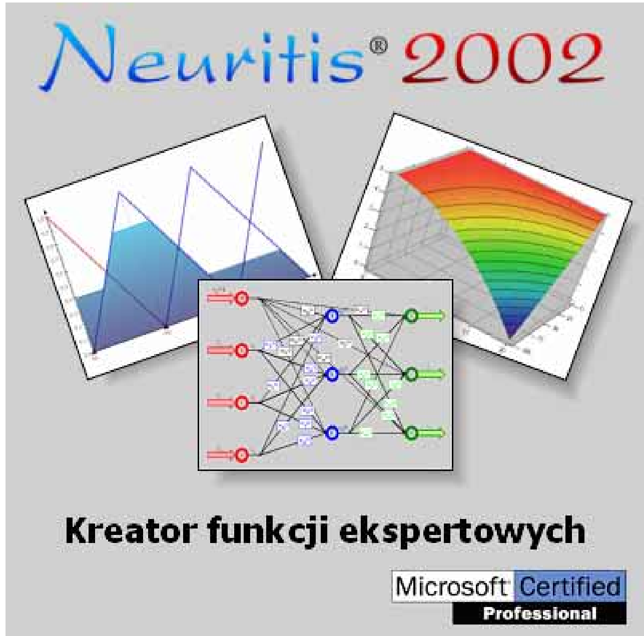


FIGURE 3 Title screen of computer system Neuritis.

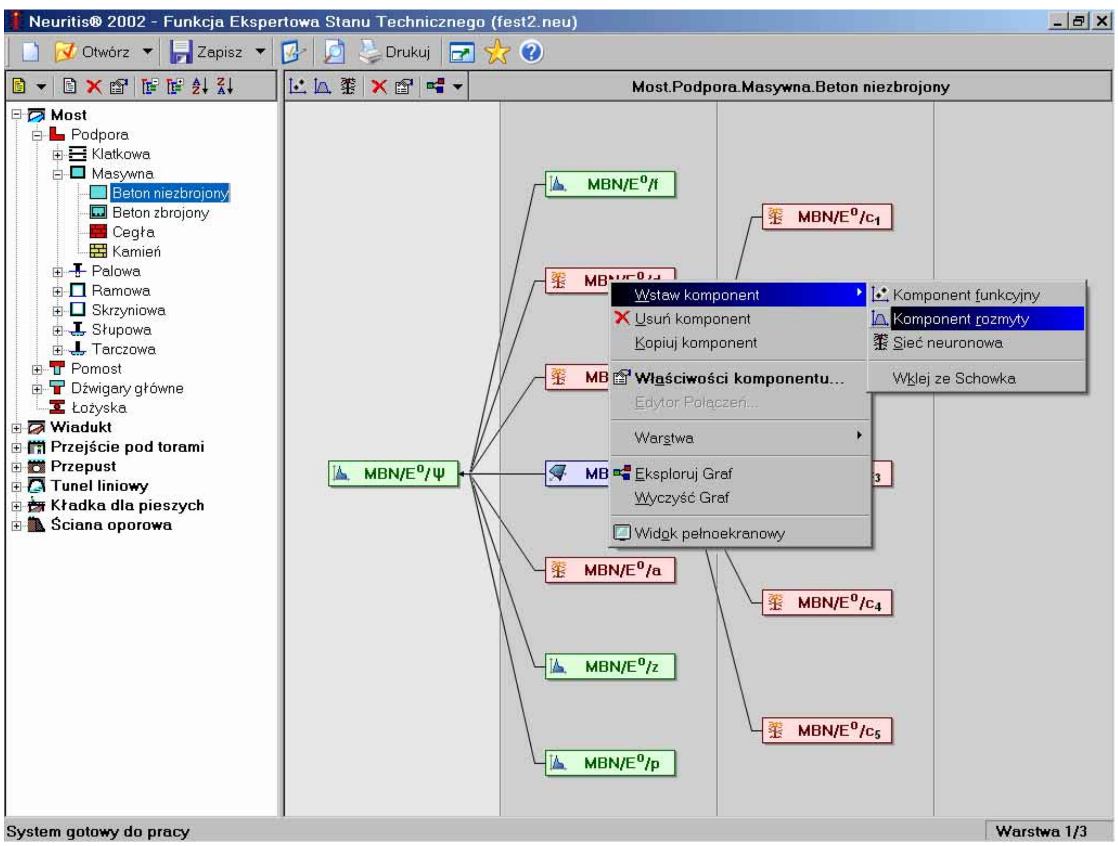


FIGURE 4 Component connection process to obtain a multilevel hybrid network.

COMPONENTS OF HYBRID NETWORKS

In the presented system Neuritis three main types of network components can be used:

- Functional components, which enable the implementation of analytical functions for knowledge representation;
- Neural components, based on the application of multilayer neural networks; and
- Fuzzy components, based on fuzzy logic and fuzzy inference methods applied for knowledge representation.

The selection of the type of components depends on the quality, quantity, and form of the available information. Each component has to be prepared individually and has to pass all the needed tests before being applied as a "brick" of the final network.

TABLE 2 Characteristics of the Hybrid Network Components Available in Neuritis

Definable elements of component		Functional component	Neural component	Fuzzy component
Input data	Form of input data	real number x_i	real number x_i	real number x_i
Input data	Form of input data	matrix of real numbers $[X_i]$		fuzzy number $\hat{x}_i$
Input data	Form of input data			linguistic variable x_i^*
Input data	Number of inputs	unlimited	unlimited	2
Internal mechanisms	Internal resources	functions of n variables in the analytic form	neural network topology	membership functions for inputs
Internal mechanisms	Internal resources	functions of n variables in the discrete form	neuron activation functions	membership functions for outputs
Internal mechanisms	Internal resources			fuzzy rule base
Internal mechanisms	Internal operations	mathematical operations on the input data	training of the neural network	aggregation of rule premises
Internal mechanisms	Internal operations			conclusion activation
Internal mechanisms	Internal operations	mathematical operations on the internal resources of the component	testing of the neural network	output composition
Internal mechanisms	Internal operations			defuzzification
Output data	Form of output data	real number y_i	real number y_i	real number y_i
Output data	Form of output data	matrix of real numbers $[Y_i]$		
Output data	Number of outputs	unlimited	unlimited	1

In the preparation of each type of components the following main steps can be distinguished:

- Defining the number of the component inputs and form of the input data;
- Defining the internal mechanisms of the component—the internal resources specific for the component and the internal operations which can be prescribed on the input data and internal resources; and
- Defining the number of the component outputs and form of the output data.

Definable elements of each type of hybrid network components are compared in Table 2. The following figures present procedures for the preparation of the main types of the network components.

The diagram of the creation process of the functional component is presented in Figure 5. Selected steps of the procedure are illustrated by the screen shots in Figure 6.

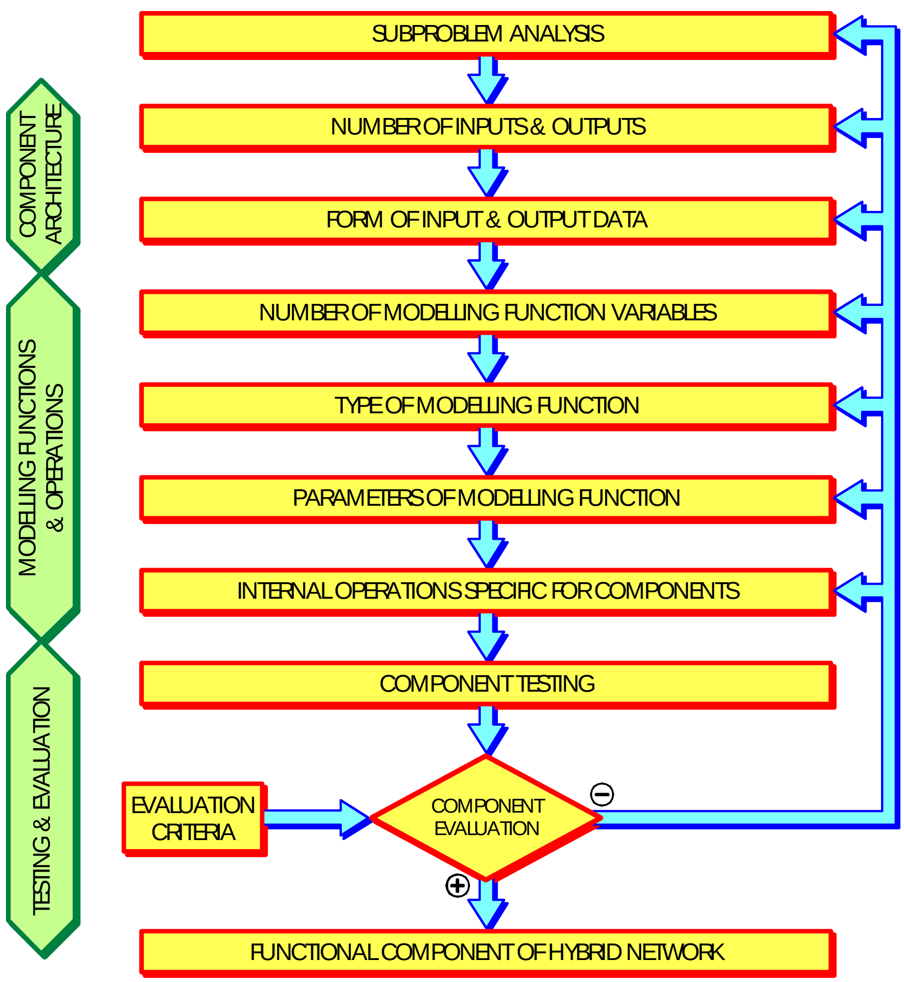


FIGURE 5 Defining procedure for a functional component of the hybrid network.

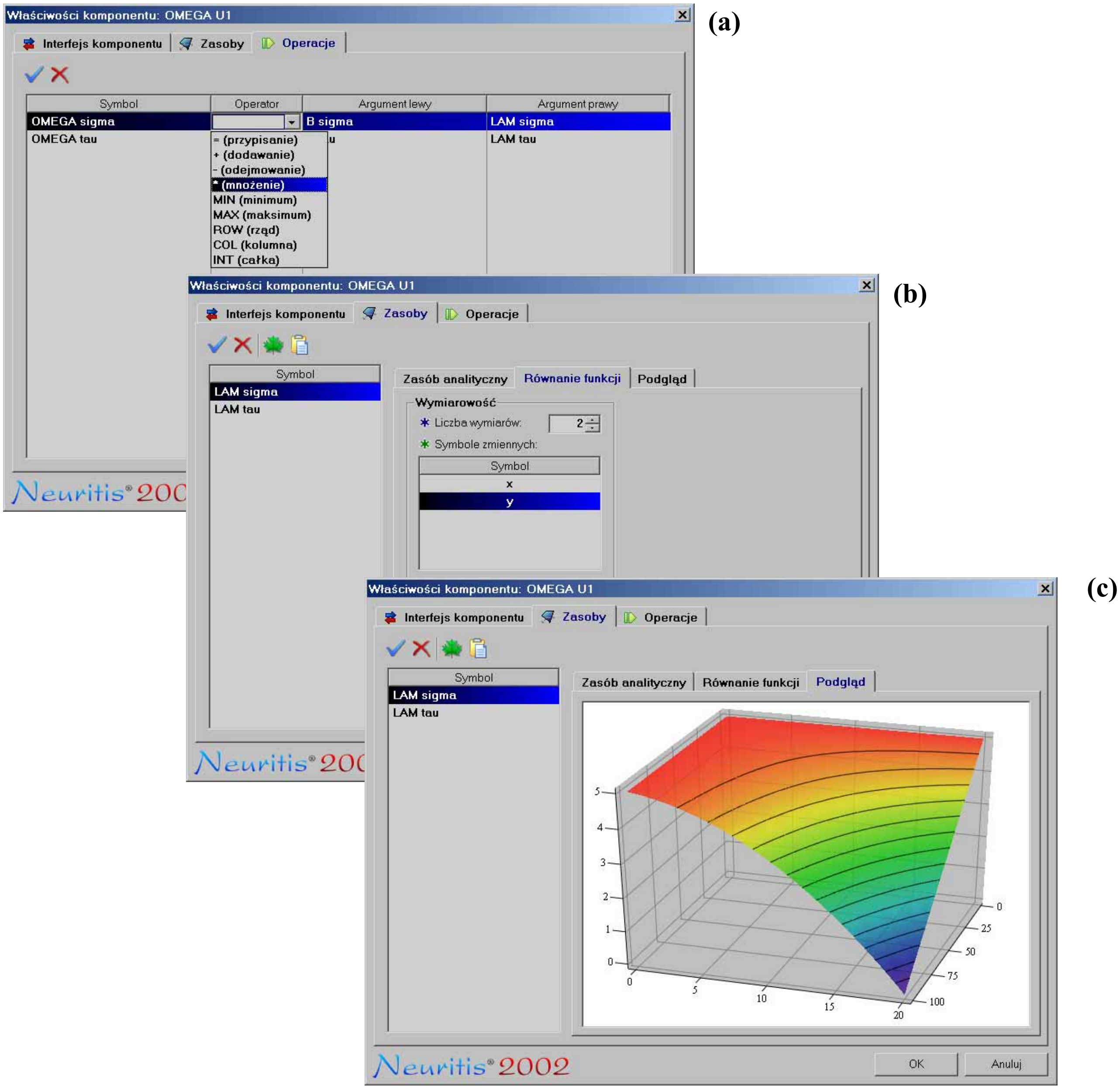


FIGURE 6 Selected steps in defining the functional component: (*a*) internal operations, (*b*) internal resources, and (*c*) visualization of internal function.

The procedure of defining the neural component is shown in Figure 7. Figure 8 presents the visualization of neural component topology in the system Neuritis.

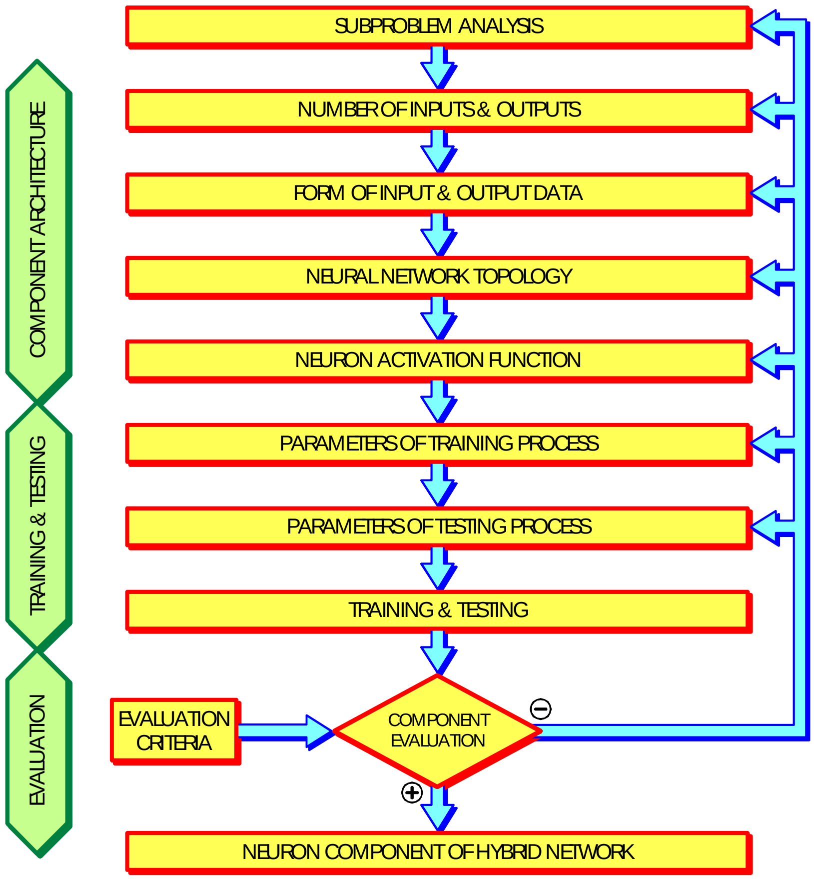


FIGURE 7 Defining procedure for the neural component of the hybrid network.

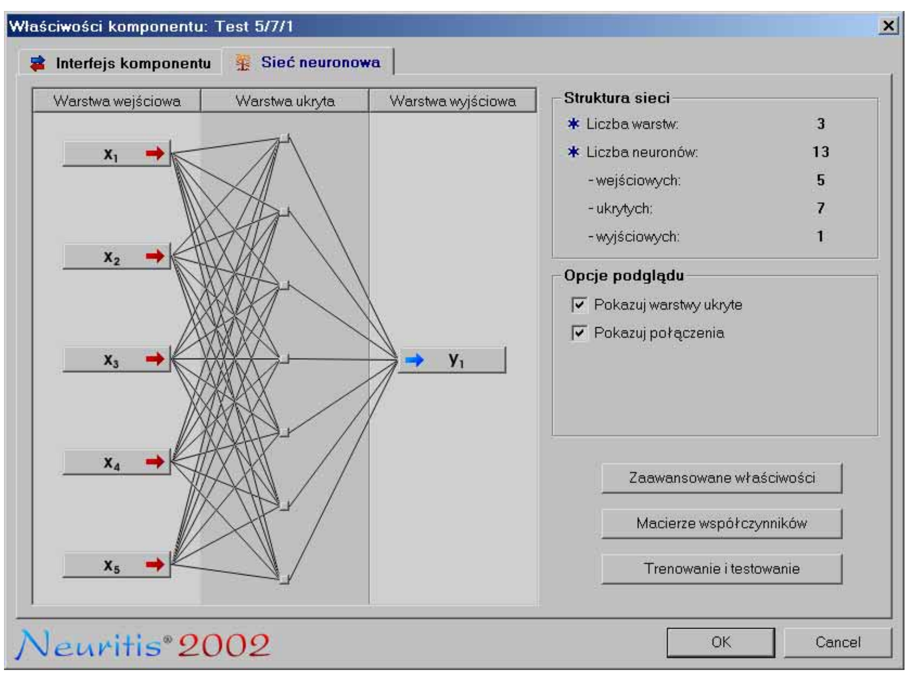


FIGURE 8 Definition of neural component topology.

Defining the fuzzy component requires specification of the fuzzy inference mechanism. The sequence of the basic steps of the component defining procedure is presented in Figure 9. The process of the fuzzy component creation in the Neuritis system is illustrated in Figure 10.

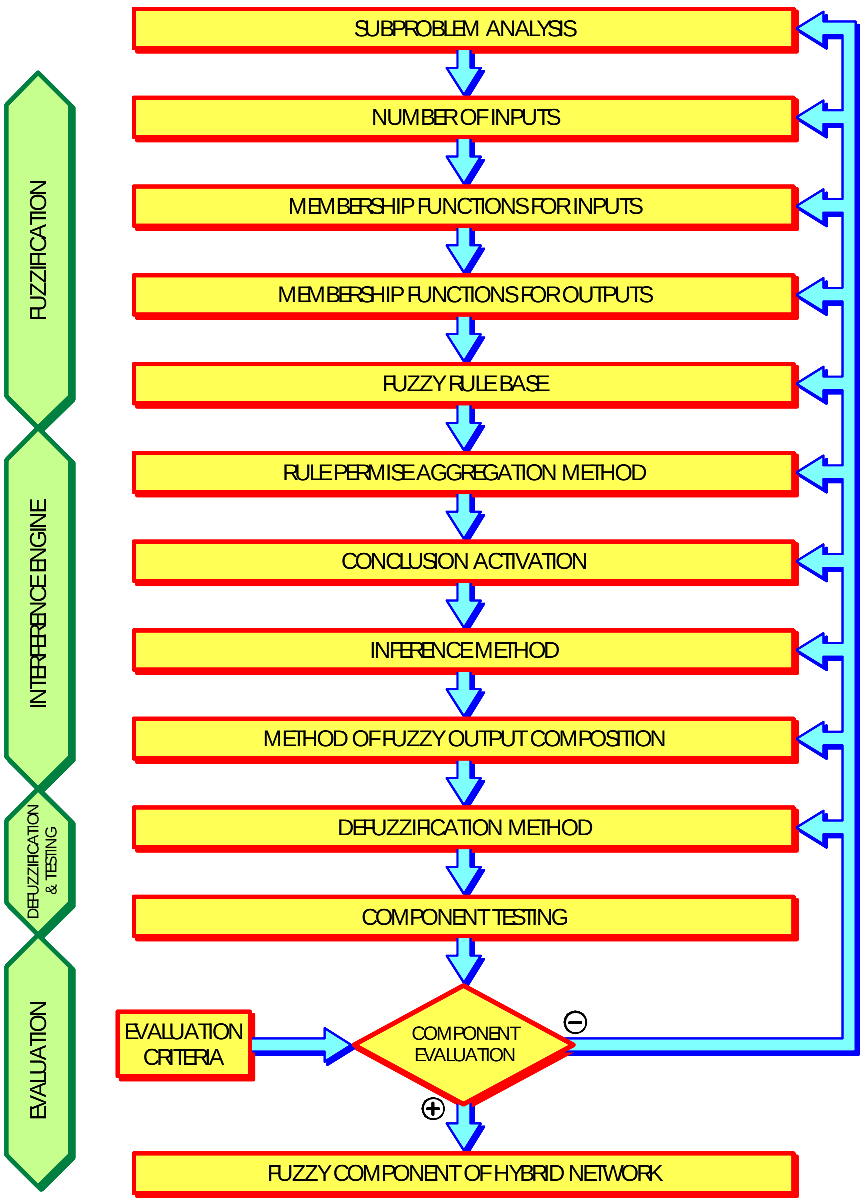


FIGURE 9 Defining procedure for the fuzzy component of the hybrid network.

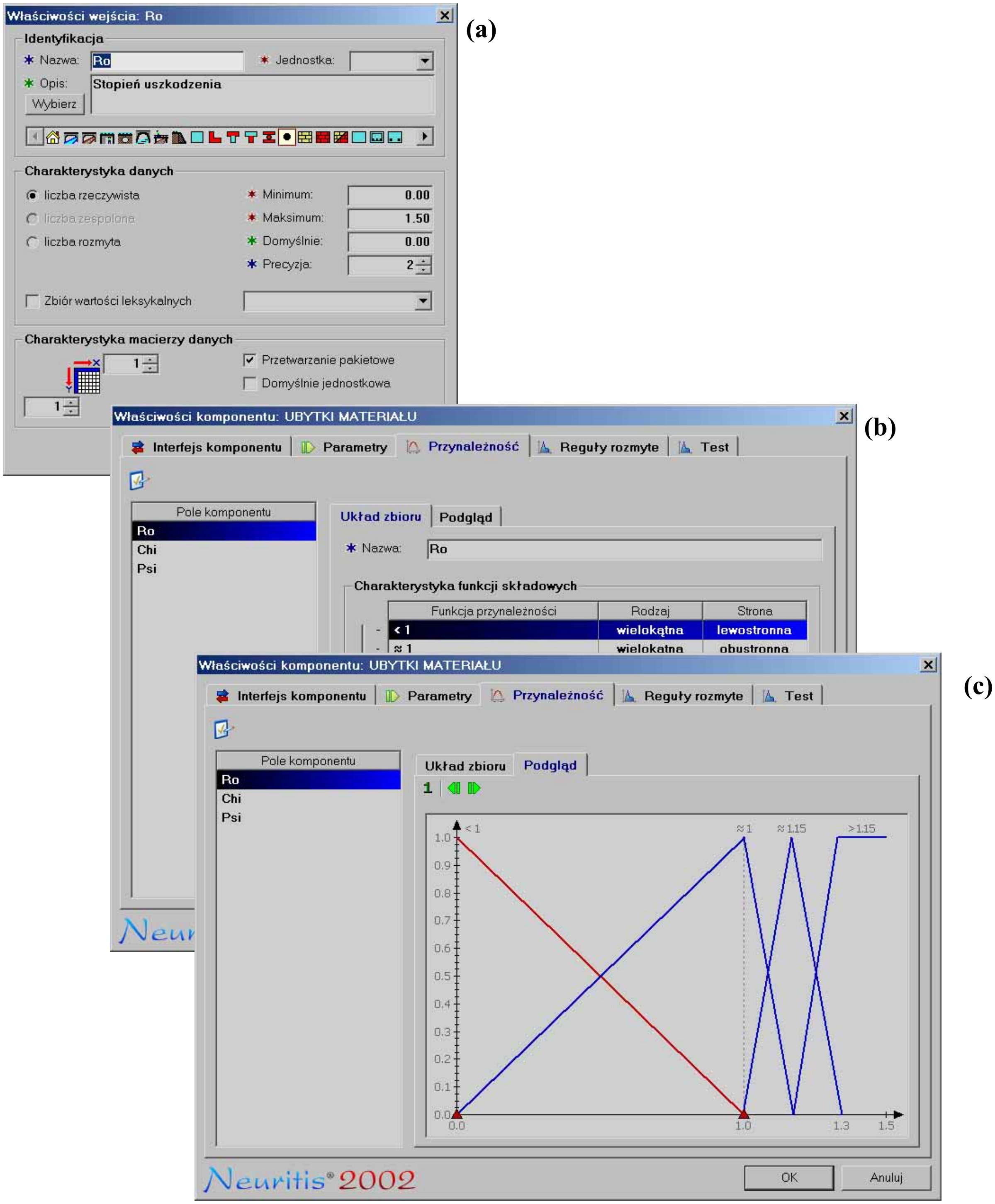


FIGURE 10 Selected steps of fuzzy component creation: (*a*) component inputs, (*b*) description of the membership functions, and (*c*) visualization of the membership functions.

APPLICATIONS IN BMS

The presented technology of knowledge representation by means of hybrid networks has been successfully applied in the Railway Bridge Management System SMOK, developed at Wroclaw University of Technology for Polish State Railways (*7*). A functional scheme of this system is presented in Figure 11, where two expert tools are shown:

- Bridge Evaluation Expert Function (BEEF): supporting evaluation of the technical condition of the main elements of bridge structures (*2*, *4*); and
- Prognosis Expert Function: aiding prediction of the bridge condition changes (*5*, *6*).

Figure 12 shows an example of the hybrid network used in BEEF for the evaluation of the Technical Condition Index (TCI) of the column bridge pier made of reinforced concrete. A three-level hybrid network has been constructed of neural, fuzzy, and functional components. The evaluation of TCI is based on the intensity and the extent of structure damages, according

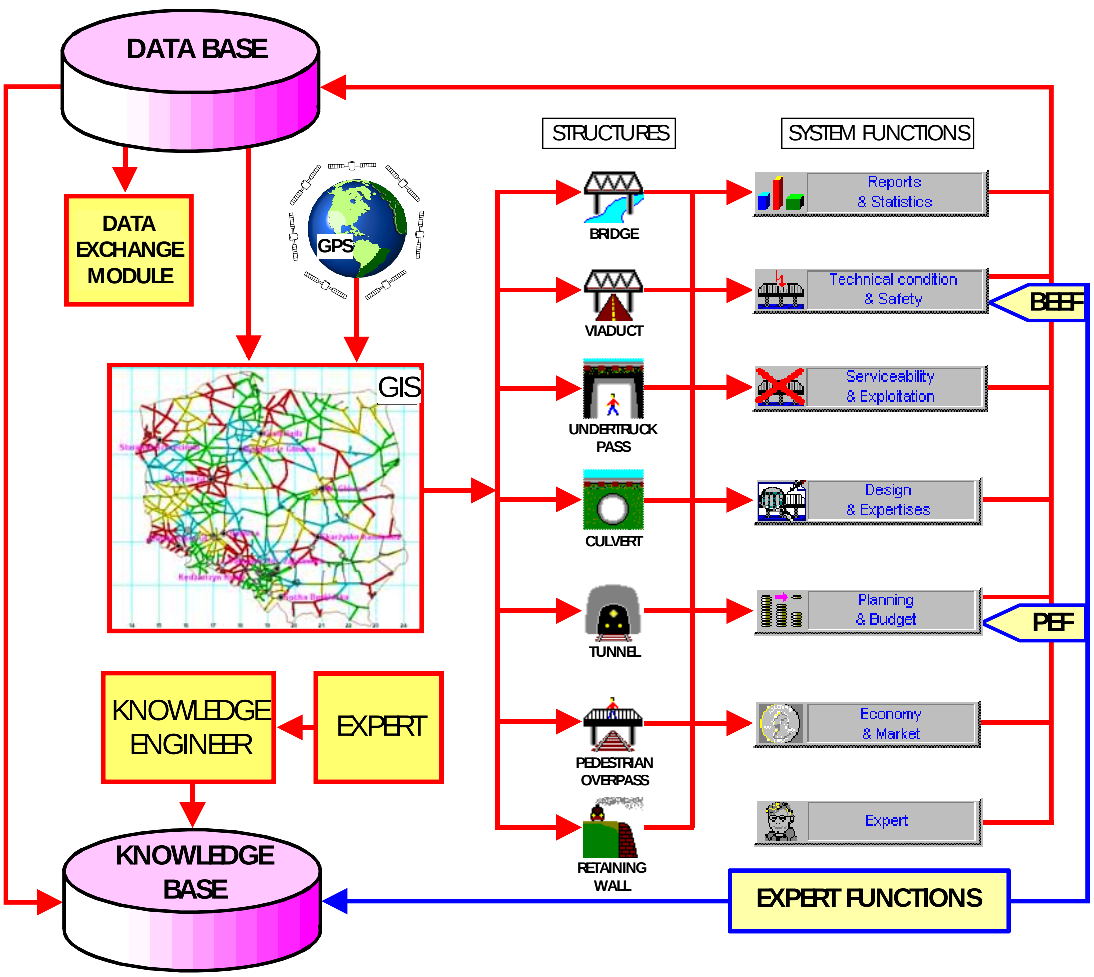


FIGURE 11 Functional scheme of the Railway Bridge Management System SMOK.

to the rules described in the Bridge Damage Catalogue (*8*). About 200 hybrid networks have been created and implemented in the whole BEEF for combinations of the following parameters:

- Type of structure (bridge, footbridge, underpass, etc.);
- Type of structure element (main girders, deck, bearings, etc.);
- Type of construction (plate, box, beam, etc.);
- Type of construction material (steel, reinforced concrete, stone, etc.).

The presented version of BEEF, as a part of the system SMOK, has been used in the bridge management offices of Polish State Railways since 2000.

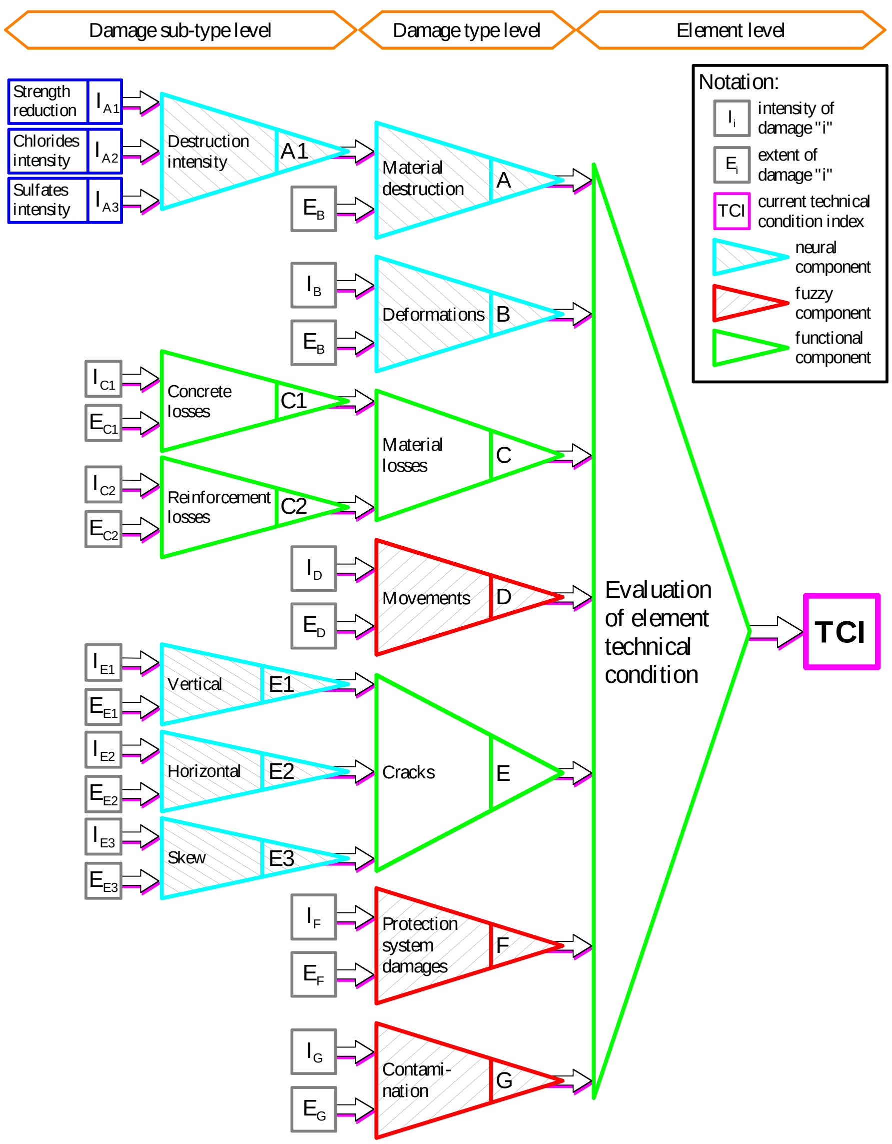


FIGURE 12 Architecture of the hybrid network used in BEEF for evaluation of TCI of the column bridge pier made of reinforced concrete.

CONCLUSIONS

The technology of multilevel hybrid networks is a powerful and effective tool of knowledge representation in BMS. The main advantages of the presented methodology of information processing and utilization can be listed as follows:

- Effective composition of the data and knowledge in the computer-based BMS;
- Integration of the diverse types of information on various levels of uncertainty in one expert tool;
- Unification of decisions in BMS due to application of specialized expert tools;
- Applications based on hybrid network technology can be easily modified by the improvement or replacement of network components, without decomposition of the whole network; and
- Technology of hybrid networks can be developed by adding new types of components and implementation of self-modification mechanisms in the components.

On the other hand, it should be underlined that the preparation of network components and the creation of practically effective networks is a very time-consuming process, engaging quite a large group of specialists. The preparation of knowledge-based expert tools for BMS requires the cooperation of civil engineering experts, knowledge engineers, computer scientists, and so on. The presented technology requires the continuation of research and extensive application study to create a more and more effective knowledge representation.

REFERENCES

1. Bień, J. *Modelling of Bridge Structures During Operation* (in Polish). Wroclaw University of Technology, Wroclaw, Poland, 2002, 348 pp.
2. Bień, J. Expert Functions in Bridge Management Systems. In *Transportation Research Circular 498: Eighth International Bridge Management Conference*. TRB, National Research Council, Washington, D.C., 2000, pp. H-3/1–15.
3. Bień, J. Neural Networks in Bridge Management Systems. Structures Congress of the American Society of Civil Engineers, Advanced Technology in Structural Engineering. Philadelphia, 2000, pp. 1–8.
4. Bień, J. Multi-Level Hybrid Networks in Bridge Management Systems. World Multiconference on Systemics, Cybernetics and Informatics, Orlando, Fla., 2001, Vol. II, Information Systems, pp. 316–321.
5. Bień, J. Hybrid Networks in Bridge Condition Evaluation and Prediction. First International Conference on Bridge Maintenance, Safety and Management, IABMAS, Barcelona, Spain, 2002, pp. 451–452 + CD.
6. Bień, J. Computer Models of Bridge Degradation Process. Expert Function Creator (in Polish). Report SPR-85/98. Wroclaw University of Technology, Institute of Civil Engineering, Wroclaw, Poland, 1998, 36 pp.
7. Bień, J. SMOK – Integrated Railway Bridge Management System (in Polish). *Inzynieria i Budownictwo*, Vol. 53, No. 3, 1996, pp. 180–184.

8. Bień, J., J. Kmita, and P. Rawa. Scientific and Technical Basis of the RBMS SMOK. Part V/9: Bridge Damage Catalogue (in Polish). Report SPR-93/98. Wroclaw University of Technology, Institute of Civil Engineering, Wroclaw, Poland, 1998.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is a division of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research results. The Board's varied activities annually engage more than 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001